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Acclimate—a model for economic damage propagation. Part II: a dynamic formulation of the backward effects of disaster-induced production failures in the global supply network

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Abstract As global warming accelerates extreme weather events such as floods, droughts and storms are likely to increase in intensity and frequency. With regard to a highly globalized world economy built on complex supply and value-added chains, this trend will challenge societies locally and globally. Regional production disruptions might induce shock waves that propagate through the global supply network and evoke supra-regional shortages. While such cascading effects are promoted by forward linkages in the global economic network, the demand-induced backward dynamics respond in a more complex way. On the one hand, backward linkages may additionally spread economic losses and thus aggravate the disaster aftermath. On the other hand, the readdressing of demand enables a readjustment of production, which may weaken or even dissipate shock waves. Here, we analyze the backward effects of disaster-induced production breakdowns by complementing the numerical damage transfer model *Acclimate* by a demand side. Based on model simulations, we show that the possibility of production extension and demand readdressing may be crucial for mitigating economic losses in the course of an extreme event.

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1 Introduction

During the last decade, there have been numerous extreme weather events: several heat waves evoking wild fires in Southern Europe (2007) and Australia (2009) as well as severe droughts in Russia (2010), East Africa (2011) and the USA (2012), major flooding of Pakistan (2010) and Thailand (2011), two once-in-a-hundred-years' floods in Central Europe (2002, 2013), devastating hurricanes Katrina (2005) and Sandy (2012) and most recently typhoon Haiyan (2013) among many others (Rahmstorf and Coumou 2012).

The IPCC (2012) special report on *Managing the Risks of Extreme Events to Advance Climate Change Adaptation* concludes that it is most probable that not only the intensity but also the number of extreme events due to global warming has increased. A significant further rise is very likely.

Besides, economic structures have changed considerably over the last decades. In the course of globalization, a complex web of international supply and value-added chains has emerged (Wiedmann et al. 2011). This global economic connectivity entails unprecedented challenges: since world markets are highly linked and local economies are increasingly dependent on international supply chains, regional extreme events may have economic repercussions in other, undamaged, parts of the world. Okuyama and Santos (2014) state that "production losses of damaged firms can potentially spread to other firms via backward and/or forward linkages, proceeding to become the ripple effect of the original loss."

The flooding of Bangkok, for instance, led to a hard disk shortage in Europe. Several coinciding extreme events in 2010 caused a rise of the world wheat price by up to 100 % potentially triggering the Arab Spring in 2011 (Sternberg 2012). In the aftermath of hurricane Katrina, gas prices increased and the 2010/11 flooding of Queensland, Australia, struck coal exports to 33 countries, inter alia troubling the German steel industry.

This kind of system-wide impacts can be referred to as higher-order effects (Rose 2004a). More precisely, following the terminology of Okuyama and Sahin (2009), hazards cause damages on stocks (physical and human capital) in affected regions. These damages can lead to first-order losses, i.e., business interruptions that cause the loss of production and consumption. Through inter-industry relationships, these losses may proceed and potentially evoke higher-order effects. Kajitani and Tatano (2014) point out that "in order to effectively reduce the losses induced by large-scale disasters in the future, it is vital to study in detail the economic losses, including the structure of complex damage propagation." With regard to an enhanced future risk of climatic extremes (Schellnhuber et al. 2012), this necessity sharpens. Bouwer et al. (2007) state that "if present trends continue, global disaster losses will keep outpacing economic growth" and suggest that "disaster risk must be core to climate adaptation policies."

The United Nation Department of Humanitarian Affairs (UNDHA 1992) defines *disaster risk* as the product of hazard and vulnerability. The concept of vulnerability to an extreme event is discussed by Van der Veen and Logtmeijer (2005). They subdivide it into three major components: the degree to which an economic activity relates to other economic activities (*dependence*), the ability of an economic activity or system to respond to a disruption by overcoming this dependence (*redundancy)* and the probability and extent of the extreme event (*susceptibility*).

Some research has already been carried out to assess the risk of future weather extremes. Peduzzi et al. (2012), for example, analyze global trends in tropical cyclone risk by taking the cumulative effects of climate change and demography into account. Mendelsohn et al. (2012) find that almost all of the tropical cyclone damage from climate change tends to be concentrated in North America, East Asia and the Caribbean/Central American region. A characterization of changes in drought risk from climate change for the USA is undertaken by Strzepek et al. (2010). Hirabayashi and Mahendran (2013) project changes in flood risk under climate change on a global scale.

To analyze economic dependencies, reliable datasets on the worldwide flows of materials, electricity and energy are required. Projects such as GTAP (Narayanan et al. 2012), WIOD (Timmer 2012), Eora (Lenzen et al. 2012) and EXIOPOL are generating comprehensive multi-regional input–output (MRIO) tables or supply-use tables (SUT) that comprise such data. Levermann (2014) recently introduced the measure *global adaptive pressure* (GAP) to express the extent to which countries depend on the direct and indirect inputs from a certain region.

The ability of an economic system to recover from a shock by overcoming such dependencies can be referred to as its resilience. Rose (2004b, 2007) contrasts static economic resilience, i.e., the capacity of a system to absorb damage or loss, with the concept of dynamic resilience that he describes as "the inherent and adaptive responses to hazards that enable individuals and communities to avoid some potential losses." While inherent resilience comprises response abilities under normal circumstances, adaptive resilience implies an extra effort to strengthen markets in view of a crisis.

Several modeling frameworks aim at analyzing resilience, evaluating vulnerability and estimating higher-order effects of natural hazards. An overview of methodologies at the macro-, meso- and microlevel to estimate the economic damage of disasters is given by Van der Veen (2004). More recent macroeconomic approaches are presented by Okuyama and Santos (2014). Basically, these are input–output (I–O) models [as in (Hallegatte 2008), (Hallegatte 2014) or (Jonkeren and Giannopoulos 2014)], social accounting matrices [SAM as in (Okuyama and Sahin 2009)] or computable general equilibrium (CGE) models [as in (Haddad and Okuyama 2012) or (Haddad and Teixeira 2013)]. An advantage of I–O models is that, since they reflect economic interdependencies, higher-order effects can easily be derived. However, given that they lack responses to price changes and are based on a Leontief production function that does not provide for a substitution of inputs [constant return to scale, see (Miller and Blair 2009) for more information], they can be attacked for "not allowing for any flexibility in the economic system" (Hallegatte 2008). The SAM approach has similar advantages and shortcomings. CGE models on the contrary assume that substitution and price responses make the economy highly adaptive. This has been criticized as an artificial way of modeling flexibility (Hallegatte 2014). In this debate between I–O and CGE models, Hallegatte presented a middle-ground approach, the adaptive regional input–output model (ARIO).

Most modeling frameworks to date have in common that they focus on analyzing the economic impact of an extreme event in the damaged region and at most a few other countries. We argue that, since regional economies are highly interconnected and links of supply chains are spread all over the world, these impact analyses are not comprehensive. We propose a nonlinear dynamic approach that focuses on the global supply network as a whole and thus comprises interregional cascading and spillover effects as well.

In the same issue of this journal, Bierkandt et al. (2014) introduce the numerical model *Acclimate*. As an availability-limited global damage transfer model, it is designed to capture the dynamic response of the global supply network to disaster-induced production failures. Embedded in a short time horizon of several days, it is up to now neither supposed to describe middle- and long-term recovery and adaptation strategies nor to reflect economic developments that are not attached to the disaster. Without an external perturbation, the model remains in equilibrium. The core of the model is the interplay of several nonlinear functions describing transactions between economic agents, namely production and consumption sites. The agents are connected to each other via inputs and, in case of a production site, outputs. The output of a production site can be reduced by an external perturbation, e.g., an extreme weather event, as well as by a lack of inputs from other production sites. Within this framework, an unanticipated local breakdown due to a climatic impact may be passed on from one production site to another and thus evoke a supra-regional supply failure. Such a cascading effect can be retarded by the existence of storages and transport-induced time delays. After a shock, each agent intends to find back to its equilibrium state.

First simulations with the basic model setup of *Acclimate* showed that cascading effects, i.e., higher-order losses, can only be avoided or reduced there if the storage capacities are high or if the perturbation time is sufficiently short (Bierkandt et al.). However, since this basic model setup does not take the demand side of an economy into account, several crucial response mechanisms are neglected: Firstly, damages may not only be passed on through forward but also through backward linkages in the economic network (Hallegatte 2008). After the Great East Japan Earthquake and the Tsunami in 2011, for instance, production decrease was partly induced by shortages of goods and partly by intermediate demand decline due to production capacity loss (Kajitani and Tatano 2014). Secondly, production sites can mitigate supply failures by readdressing their demand to nonaffected suppliers. Referring to (Van der Veen and Logtmeijer 2005), the ability of a system to overcome its dependencies by such a readdressing essentially alleviates its vulnerability. Thirdly, production sites can react to a crisis by adjusting their production. On the one hand, they can reduce their output if their products are less requested. This situation may arise if they are supplying regions or industries affected by the extreme event. On the other hand, they are, to a certain extent, able to increase their production to replace competitors hit by the disaster. Following the concepts of (Rose and Dongsoon 2002) and (Cochrane 1997) on direct and indirect disaster costs, the possibility of production extension, together with the availability of alternative resources and the duration of the disaster, determines the magnitude of the indirect effects of an extreme event (Van der Veen 2004).

While some of these aspects may lead to an aggravation of the disaster, i.e., affected production sites pass the damage not only to purchasers but also to suppliers, the readdressing of demand and the extension of production ratios might enable a capturing or at least weakening of shock waves in the global supply network (dissipation effect). Hence, the nonconsideration of the demand side of an economy implies a potential over- or underestimation of the economic impact of an extreme event. Therefore, we extend the basic setup of the global damage model *Acclimate* by a demand side (Sect. 2). Subsequently, we investigate its performance in different disaster scenarios with particular focus on potential dissipation effects due to production extension and demand redistribution (Sect. 3). We then outline strengths and limitations of our model and conclude with an overview on further add-ons (Sect. 4).

2 Model description

For completeness, we give a short review of the basic setup of the numerical damage transfer model *Acclimate* as detailed in (Bierkandt et al.) before we extend it by a dynamic formulation of demand determination and distribution.[1] A comprehensive list of all agents and parameter of our modeling framework including their units can be found in Appendix 1.

2.1 Basic model setup

Let the index-pair, *js,* represent an arbitrary production site where *j* denotes the good being produced (or an economic sector) and *s* the region the site is located in. This production site is connected to other regional industries *ir* and *ku* through monetary flows $Z^{(t)}_{ir\rightarrow js}$ (inputs) and $Z^{(t)}_{js\rightarrow ku}$ (outputs) at time step (t). The initial flows $Z^{*}_{ir\rightarrow js}$ and $Z^{*}_{js\rightarrow ku}$ (in currency per time) at time step ($t = 0$) can be derived from MRIO tables (baseline of the model). We introduce dynamics on these flows using discrete time steps of lengthΔt that we choose to be one day. To make the interaction between *js* and other regional production sites more realistic, we introduce a transport-induced time delay as follows: Let $\tau_{ir\rightarrow js}$ represent the transit time in time steps, i.e., the time it takes to transport good *i* from region *r* to regional sector *js*. We assume that the transportation path is subdivided into $\tau_{ir\rightarrow js}$ discrete sections *b* so that

[1] An implementation of the basic and extended model set-up is available upon request.

transport section stock $T^{(t+1)}_{ir \underset{b}{\rightarrow} js}$ describes how much of good i from region r that is conveyed to js is located in section b at time step $(t+1)$:

$$T^{(t+1)}_{ir \underset{b}{\rightarrow} js} = Z^{(t+1-b)}_{ir \rightarrow js} \cdot \Delta t \quad \forall b \in \left[0, \tau_{ir \rightarrow js} - 1\right]. \tag{1}$$

This concept enables us to eventually study a destruction of infrastructure and goods during transportation. The total amount of good i from region r that is shipped or trucked to production site js at time step $(t+1)$, i.e., the transport stock, is thus given by

$$T^{(t+1)}_{ir \rightarrow js} = \sum_{b=0}^{\tau_{ir \rightarrow js}-1} T^{(t+1)}_{ir \underset{b}{\rightarrow} js}. \tag{2}$$

All goods i arriving at production site js at time step $(t+1)$ add up to its total input flow of good i:

$$I^{(t+1)}_{i \rightarrow js} = \frac{1}{\Delta t} \sum_{r'} T^{(t+1)}_{ir' \underset{b(r')}{\rightarrow} js}; \quad b(r') = \tau_{ir' \rightarrow js} - 1. \tag{3}$$

This input is stored in the input storage $S^{(t+1)}_{i \rightarrow js}$ for good i. The content of this storage is assumed constant unless the amount $U^{(t)}_{i \rightarrow js}$ of goods i that was used for the last production differs from the number of inputs at that time. Additionally, an external perturbation can lower the storage content. This perturbation is expressed in terms of a forcing $\mu^{(t+1)}_{i \rightarrow js} \in [0,1]$. The initial storage content $S^{*}_{i \rightarrow js} = \psi_i \cdot I^{*}_{i \rightarrow js}$ is a multiple of the initial input flow $I^{*}_{i \rightarrow js}$ and may be exceeded at most by an upper limit factorω_i. The parameter ψ_i expresses for how many days ψ_i a production site can keep its production up if input i is lacking.

The storage content at time step $(t+1)$ can hence be calculated as follows:

$$\begin{aligned} S^{(t+1)}_{i \rightarrow js} = \max\Big(\min\Big(&\mu^{(t+1)}_{i \rightarrow js} \cdot \omega_i \cdot S^{*}_{i \rightarrow js}, S^{(t)}_{i \rightarrow js} \\ &+ \Delta t\Big(I^{(t)}_{i \rightarrow js} - U^{(t)}_{i \rightarrow js}\Big)\Big), 0\Big). \end{aligned} \tag{4}$$

For its production, js uses its current inputs. If these inputs are not sufficient, it can revert to its input storages. The amount of any good i that can be used for production at time step $(t+1)$ is thus given by

$$\hat{U}^{(t+1)}_{i \rightarrow js} = I^{(t+1)}_{i \rightarrow js} + \frac{S^{(t+1)}_{i \rightarrow js}}{\Delta t}. \tag{5}$$

The possible use $\hat{U}^{(t+1)}_{i \rightarrow js}$ of good i has to be compared to the possible use of all other inputs $j \neq i$. We assume that if one intermediate input is reduced by a certain factor, the whole output has to be reduced by the same factor (*perfect complementarity*). Given the short time horizon, we do not allow for substitution of goods. To refine the model, substitution elasticities could be introduced. Furthermore, a classification of goods that distinguishes between investment goods for which the assumption of perfect complementarity does not hold and intermediate inputs could be implemented. Such a classification is especially reasonable if there are a large variety of different sectors.

In the basic model setup, we assumed that the initial production ratio $p^{*}_{js} = 1$ cannot be surpassed. To allow for a situational exceeding of ratio p^{*}_{js}, we now introduce the production extension factor $\beta_{js} \geq 1$ that represents the maximal production ratio production site js can achieve. This upper ratio can be reduced by an external forcing $\lambda^{(t+1)}_{js}$. Considering production facilities, forcing, inputs and storage content, we obtain the following possible production ratio at time step $(t+1)$:

$$\hat{p}^{(t+1)}_{js} = \min\left(\min_i\left(\frac{\hat{U}^{(t+1)}_{i \rightarrow js}}{U^{*}_{i \rightarrow js}}\right), \lambda^{(t+1)}_{js} \cdot \beta_{js}\right). \tag{6}$$

Since it is reasonable to produce not only input-driven but also in accordance with the current market, we now introduce a target production ratio $\tilde{p}^{(t+1)}_{js}$, reflecting the demand side. It will then, together with $\hat{p}^{(t+1)}_{js}$, determine the actual production ratio $p^{(t+1)}_{js}$.

2.2 Integration of demand side

In the following, we complement the basic model setup by dynamics capturing demand determination and distribution. Let ku represent another production site, which uses good j as an input for its production. Its demand for j at time step (t) is given by

$$D^{(t)}_{j \leftarrow ku} = \max\left(\tilde{U}^{(t)}_{j \rightarrow ku} + \frac{\left(S^{*}_{j \rightarrow ku} + \sum_s T^{*}_{js \rightarrow ku} - S^{(t)}_{j \rightarrow ku} - \sum_s T^{(t)}_{js \rightarrow ku}\right)}{\gamma_j}, 0\right); \tag{7}$$

where $\tilde{U}^{(t)}_{j \rightarrow ku}$ denotes the target or desired use of good j at time (t):

$$\tilde{U}^{(t)}_{j \rightarrow ku} = \tilde{p}^{(t)}_{ku} \cdot \lambda^{(t)}_{ku} \cdot U^{*}_{j \rightarrow ku}. \tag{8}$$

The target used flow $\tilde{U}^{(t)}_{j \rightarrow ku}$ reflects how much of good j was or would have been necessary in order to produce according to the target production ratio $\tilde{p}^{(t)}_{ku}$, considering the imposed forcing $\lambda^{(t)}_{\mathrm{ku}}$ at that time. The target production ratio that will be defined by Eq. (12) describes the amount of output required for fulfilling all demand requests. Ideally, it equals the possible production ratio $\hat{p}^{(t+1)}_{ku}$ (Eq. 6). If this is not the case, i.e., if the production site cannot fulfill all demand requests, this may be due to missing inputs and/or due to a reduced production ratio. In case of missing inputs, the factor $\tilde{p}^{(t)}_{ku} \cdot U^{*}_{j \rightarrow ku}$ addresses this lack. In the latter case, the factor $\lambda^{(t)}_{\mathrm{ku}}$ guarantees that the desired used flow $\tilde{U}^{(t)}_{j\to\mathrm{ku}}$ does not exceed the amount of input j that could actually be processed.

Equation (7) is motivated by the following consideration: As long as the storage content (including transport boxes) remains constant, the demand of *ku* for *j* at time step (t) equals $\tilde{U}^{(t)}_{j\to ku}$. In case the storage content changed, the demand is employed to balance the difference. If the stock decreased, the demand increases in order to refill the storage whereat the storage refill time γ_j regulates the rate at which this replenishment takes place. If by contrast the storage content increased, i.e., if *ku* did not use all its inputs *j*, the demand decreases. Since the carryover was stored, it can be used in the next time steps and does not have to be requested. The content of transport boxes is considered as future inputs and is thus included into the planning scheme.

2.3 Dynamic formulation of demand distribution

Once the demand of *ku* for good *j* is determined, it has to be addressed to one or more production sites offering this good. Here, we assume that all links within the global supply network are fixed. This implies that only production sites connected through initial flows can communicate with each other.

We propose that production site *ku* (i.e., its purchasing manager) distributes its demand for good *j* among its suppliers according to the following scheme:

$$D^{(t)}_{js\leftarrow ku} = \frac{\theta^{(t)}_{js\to ku}\cdot Z^{*}_{js\to ku}}{\sum_{s'}\theta^{(t)}_{js'\to ku}\cdot Z^{*}_{js'\to ku}}\cdot D^{(t)}_{j\leftarrow ku}. \qquad (9)$$

The amount of demand, $D^{(t+1)}_{js\leftarrow \mathrm{ku}}$, production site *js* receives is determined by a demand–supply history $\theta^{(t)}_{js\to\mathrm{ku}}$ recursively describing how well *js* has fulfilled former demand requests of *ku*:

$$\theta^{(t)}_{js\to\mathrm{ku}} = \varphi\cdot\theta^{(t-1)}_{js\to ku} + (1-\varphi)\cdot\vartheta^{(t)}_{js\to ku};\quad \varphi\in]0,1]; \qquad (10)$$

where

$$\vartheta^{(t)}_{js\to ku} = \frac{Z^{(t)}_{js\to ku}}{D^{(t-1)}_{js\leftarrow ku}}. \qquad (11)$$

By means of the history weight φ, different strategies of demand distribution can be pursued. For $\varphi = 1$, only the initial demand–supply ratio $\vartheta^{*}_{js\to ku}$ is considered while for $\varphi < 0.5$ more importance is conceded to the last delivery than to former demand–supply ratios. In Sect. 3, we will analyze the performance of several demand distribution strategies under different scenarios.

Other demand distribution strategies will be introduced in forthcoming model versions. By then, the model will have been extended by price dynamics and the possibility of a rewiring of the network structure. Purchasing managers will be able to distribute their demand not only according to their suppliers' reliability (i.e., the demand–supply history) but also dependent on the prices they offer. Moreover, they will be able to give up expensive or unreliable suppliers and establish new business connections.

2.4 Consolidation of supply and demand side to determine local production

We can now conclude the computation of regional sector *js*'s production (see Fig. 1 for a schematic illustration). The demand requests $D^{(t)}_{js\leftarrow ku}$ that *js* (i.e., its "Production Manager") receives from different purchasers, *ku*, are used to determine its target production ratio $\tilde{p}^{(t+1)}_{js}$:

$$\tilde{p}^{(t+1)}_{js} = \frac{\sum_{k'}\sum_{u'} D^{(t)}_{js\leftarrow k'u'}}{X^{*}_{js}}; \qquad (12)$$

where $X^{*}_{js} = \sum_{k'}\sum_{u'} Z^{*}_{js\to k'u'} = \sum_{k'}\sum_{u'} D^{*}_{js\leftarrow k'u'}$ denotes its

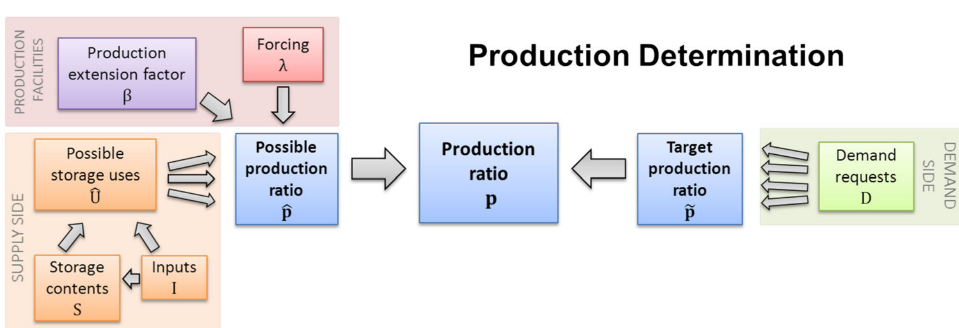

Fig. 1 *Production determination*. A regional sector's production is determined by its facilities, its supply and incoming demand requests: While the possible production ratio reflects the current capacities considering recent inputs, storage contents, production extension capability and forcing, the target production ratio accounts for the latest incoming demand requests

initial production. Considering the possible production ratio $\hat{p}_{js}^{(t+1)}$ as described in Sect. 2.1, the production ratio is obtained as follows:

$$p_{js}^{(t+1)} = \min\left(\tilde{p}_{js}^{(t+1)}, \hat{p}_{js}^{(t+1)}\right). \tag{13}$$

Accordingly, js's production at time step $(t + 1)$ is given by

$$X_{js}^{(t+1)} = p_{js}^{(t+1)} \cdot X_{js}^{*}. \tag{14}$$

The production $X_{js}^{(t+1)}$ has to be distributed among all buyers. Again, there are several distribution strategies that could be thought of as favoring certain buyers over others. Such approaches as well as their potential interactions with the different demand distribution strategies have to be discussed separately and are not part of this paper.

Here, we apply a simple scheme that implies that production site js (i.e., its "Sales Manager") distributes the output equally according to the received demand requests among all buyers including itself:

$$Z_{js\to ku}^{(t+1)} = \frac{D_{js\leftarrow ku}^{(t)}}{\sum_{k'}\sum_{u'} D_{js\leftarrow k'u'}^{(t)}} \cdot X_{js}^{(t+1)}. \tag{15}$$

If js's output is reduced by a certain factor, this damage factor is passed on equally to each of its buyers.

Figure 2 provides a schematic illustration of a production site's functionality in the extended model setup.

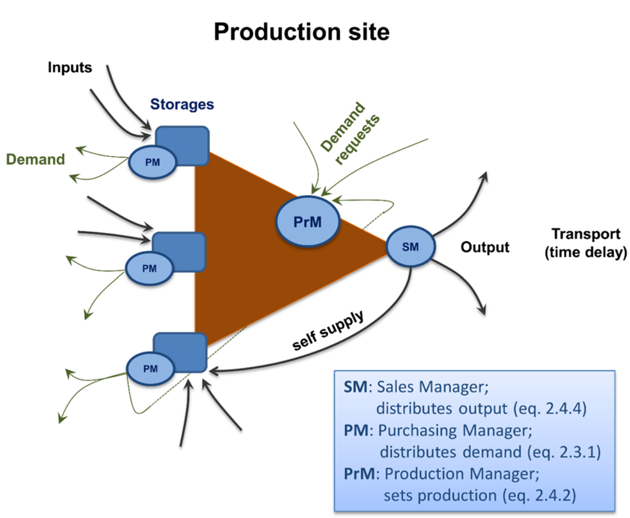

Fig. 2 *Schematic illustration of model setup*. A production site is connected to other economic agents as well as to itself through inputs and outputs considering transport-induced time delays. The managers take decisions: The "Production Manager" (PrM) fixes the current production in accordance with the input storages' contents and the demand for the product. "Sales Manager" (SM) and "Purchasing Manager" (PM) decide on output and demand distribution, respectively

2.5 Final demand, GDP and value added

The model description has not included final demand flows and consumption sites so far. Generally, the final demand of a region is defined as its household consumption, government spending and investments. A final demand flow $Z_{ir\to j_f s}^{*}$ (i.e., a flow from an arbitrary production site ir to the final demand "sector" j_f of a region s) is also given by multi-regional input–output tables. A consumption site can roughly be regarded as another, slightly modified, production site of region s. Analogous to a production site, a consumption site has input storages and addresses demand requests. Instead of a production ratio, it consumes a good i according to a certain consumption ratio:

$$c_{i\to j_f s}^{(t+1)} = \min\left(\frac{\hat{U}_{i\to j_f s}^{(t+1)}}{U_{i\to j_f s}^{*}}, \lambda_{i\to j_f s}^{(t+1)}\right); \tag{16}$$

where $\lambda_{i\to j_f s}^{(t+1)}$ describes the external forcing that can be imposed upon consumption. This forcing reflects changes in consuming patterns due to an extreme event. The assumption of perfect complementarity is not applied here. The total amount of good i that consumption site j_f consumes at time $(t + 1)$ is thus given by

$$C_{i\to j_f s}^{(t+1)} = U_{i\to j_f s}^{(t+1)} = c_{i\to j_f s}^{(t+1)} \cdot U_{i\to j_f s}^{*}. \tag{17}$$

In this model setup, consumption sites are included into the output distribution scheme of a production site as equal buyers. It is also possible to think of a social pressure strategy that prioritizes consumption sites over other economic agents or the other way around.

The final demand flow of a country is closely connected to its GDP:

$$\begin{aligned} \text{GDP} &= \text{private consumption} + \text{government spending} \\ &\quad + \text{gross investments} + \text{exports} - \text{imports} \\ &= \text{final demand} + \text{exports} - \text{imports}. \end{aligned}$$

Within an input–output framework, the right side of this equation corresponds to the difference between all outputs and all inputs, i.e., the value added (including taxes), of the region (see Appendix 2). Accordingly, the GDP of a country equals its total value added.

3 Performance of the model under idealized perturbations

In this section, we aim at understanding the basic numerical performance of the extended model *Acclimate* in idealized scenarios as a basis for future studies. We do not intend to hind- or forecast economic losses of real extreme events here but focus on theoretically analyzing the demand-induced backward dynamics of a production failure, their interaction and how they possibly reinforce or mitigate shock waves in the global supply network.

In order to yield a valid representation of the global supply network, we use multi-regional input–output data provided by Eora (Lenzen et al. 2012) for the year 2009. These data describe annual economic transactions (in US \$) between 27 sectors (including final demand) in 186 regions. Hence, a network of 4,836 production and 168 consumption sites (nodes) that are connected via input and output flows (links, in US \$ per day) can be built. After having filtered all flows that are smaller than 1 million US \$ per year, the network consists of about 500,000 links.

The transit times for the model simulations are derived from capital distances and an associated average velocity of transport medium provided by (Sea Rates 2013): If the distance is less than 3,000 km, we expect a transport by truck at an average speed of 35 km/h. For distances higher than 3,000 km, we consider a transport by vessel at 20 km/h (see (Bierkandt et al.) for more detail). These transit times are used for all simulations unless indicated otherwise.

We assume that a sector in Japan breaks down for ten days and examine which economic consequences, i.e., production and consumption losses as well as changes in storage contents, *Acclimate* shows for this scenario. Particularly, we examine how these consequences vary in dependence on the demand-related parameter and response mechanisms. In Sect. 3.1, we investigate if and in how far production failures propagate through backward linkages in the economic network. We then give an overview on the potential dissipative effects of production extension and demand readdressing in Sect. 3.2 before we analyze them in more detail in Sects. 3.3 and 3.4.

Our simulations are restricted to Japan for different reasons. Firstly, it is geographically exposed and was recently subject to extreme events. Secondly, the Japanese economy is industrialized and internationally strongly connected. Finally, as it is a rather small country, even on an aggregate data level, a quite precise scenario formulation is possible.

3.1 Comparing forward and backward propagation of economic losses

In this subsection, we analyze the backward, i.e., upstream against the economic supply flow, propagation of disaster-induced production failures in the economic network based on *Acclimate* simulations. Particularly, we compare and contrast it to the (forward) cascading effects observed in (Bierkandt et al.). In order to better condensate if and in how far production failures are passed on via backward linkages, we neither allow for production extension ($\beta = 1$), nor for a

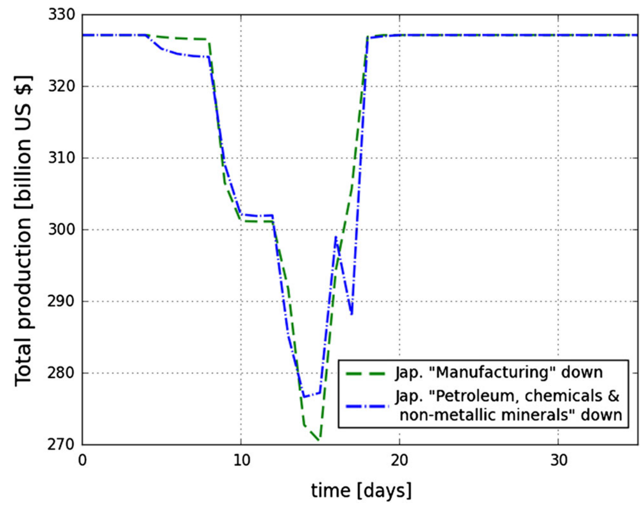

Fig. 3 *Direct and indirect production losses*. The Japanese "Manufacturing" and "Petroleum, chemicals and nonmineral products" sectors are assumed to stop production from day 5 until day 14, respectively. In the following, the worldwide production level temporarily decreases due to cascading supply shortages and demand reductions

readdressing of demand, i.e., with $\varphi = 1$ only the initial demand–supply ratio determines the distribution of demand. Additionally, we do not consider transport-induced time delays ($\tau = 1$ day). With regard to storage capacities, we assume that each production and consumption site has input storages that last for $\psi = 3$ days. These initial storage capacities can be surpassed by a factor$\omega = 2$. The storage refill time is set to $\gamma = 10$ days. We impose a forcing on varying Japanese sectors such that each cannot produce from day 5 to day 14 ($\lambda^t = 0 \quad \forall t \in [5, 14]$). As an example, Fig. 3 shows the worldwide production decrease in billion, i.e., 10^9, US Dollar caused by a breakdown of the Japanese "Manufacturing" and "Petroleum, chemicals and nonmineral products" sectors, respectively. In the course of these events, several other production sites temporarily decreased their production because they were directly or indirectly connected to the affected sector.

In both cases, the production reductions are predominately caused by a decline of demand requests (i.e.$\tilde{p} < 1$) rather than a lack of inputs ($\hat{p} < 1$). The right column of Fig. 4 shows that if the Japanese "Manufacturing" sector is assumed to stop production for ten days, 93.1 % of all production reductions occurring during these and the following five days are caused by a decline of demand requests, whereas only 6.9 % are due to a lack of inputs. If the sector "Petroleum, chemicals and nonmineral products" is chosen to break down (left column of Fig. 4), this discrepancy even sharpens. In order to avoid numerical artefacts, we rounded numbers at a precision of 10^{-3}. An explanation for the discrepancy is that the propagation of

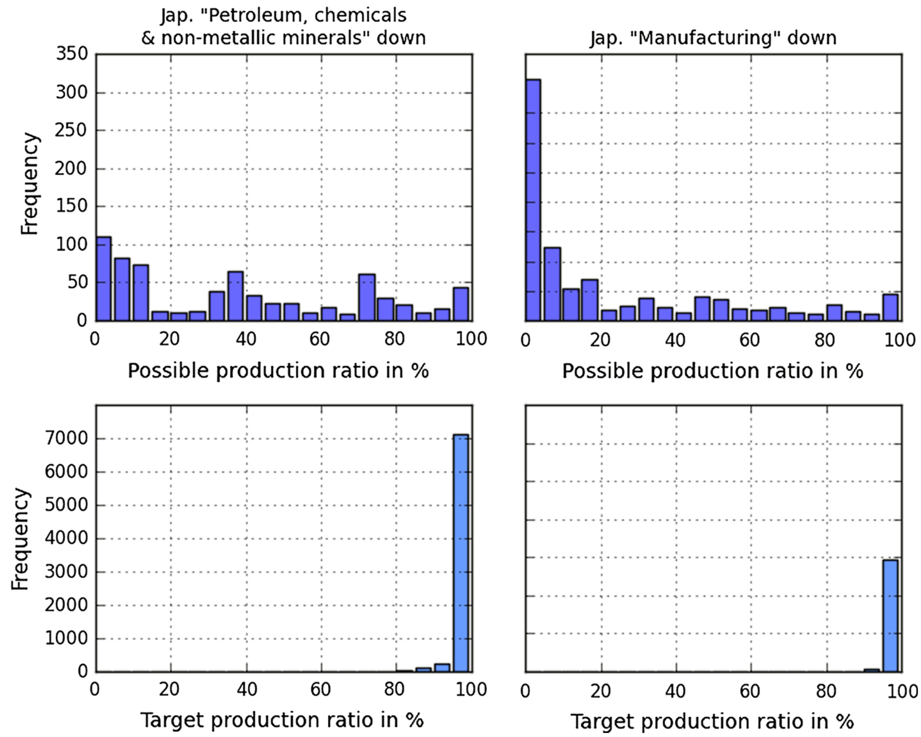

Fig. 4 *Comparison of economic loss propagation through forward and backward linkages: frequency distribution of possible and targetproduction ratio during 20 days*. In the *left column*, the Japanese "Petroleum, chemical and nonmetallic mineral products" sector and, in the *right column*, the Japanese "Manufacturing" sector are assumed to break down for ten days (days 5–14). If the target production ratio (reflecting the demand side) is decreased, then this is, in both scenarios, mostly by less than 5 % and at least by 40 %. If the possible production ratio (reflecting the supply side) is affected, then the decrease is most often up to 90–100 %

losses through forward linkages is weakened by the existence of storages while they can be passed on immediately via backward linkages.

However, if we also take the magnitude of the production losses into account, we find that the demand-induced losses are significantly smaller than those evoked by supply shortages. Figure 4 shows that the target production ratio is mostly reduced by less than 5 % and at least by 40 %, whereas the possible production ratio peaks at a 90–100 % reduction. This finding is also confirmed by simple calculations based on model equations. If an arbitrary node js is assumed to break down and if $d^{\text{forward}}_{js\rightarrow ku}$($d^{\text{backward}}_{ir\leftarrow js}$) describes the damage ratio that is passed on via a forward (backward) linkage to another node ku (ir), we get:

$$d^{\text{forward}}_{js\rightarrow ku} = \frac{Z^*_{js\rightarrow ku} - Z^{(t)}_{js\rightarrow ku}}{\sum_{s'} Z^*_{js'\rightarrow ku}}$$

and

$$d^{\text{backward}}_{ir\leftarrow js} = \frac{D^*_{ir\leftarrow js} - D^{(t)}_{ir\leftarrow js}}{\sum_{j'}\sum_{s'} D^*_{ir\leftarrow j's'}} = \frac{Z^*_{ir\rightarrow js} - \overbrace{D^{(t)}_{ir\leftarrow js}}^{\geq Z^{(t+1)}_{ir\rightarrow js}}}{\sum_{j'}\sum_{s'} Z^*_{ir\rightarrow j's'}} \leq \frac{Z^*_{ir\rightarrow js} - Z^{(t+1)}_{ir\rightarrow js}}{\sum_{j'}\sum_{s'} Z^*_{ir\rightarrow j's'}}$$

Generally, the damage that is passed on from js to ir via a backward connection is thus smaller than the damage would have been if js was affected and had forwarded the damage through the same edge to js (dependent on the underlying network structure). This difference is due to the assumption of perfect complementarity: While the demand reduction $\left(D^*_{ir\leftarrow js} - D^{(t)}_{ir\leftarrow js}\right)$ caused by a breakdown of js is divided by the sum of all demand requests ir receives, the reduction in supply $\left(Z^*_{js\rightarrow ku} - Z^{(t)}_{js\rightarrow ku}\right)$ is only calibrated by the sum of all other inputs j that ku gets.

3.2 Overview on dissipation mechanisms

After having discussed the damage propagation of production failures through backward linkages, we now investigate the potentially weakening or dissipative effects associated to the demand dynamics of *Acclimate*. By weakening effects, we refer to mechanisms that may 1) reduce the second and higher-order economic losses induced by an extreme event and 2) enable a complete recovery of the system that was not possible so far. We thereby focus on two mechanisms: the readdressing of demand requests to other, nonaffected producers of the required good and the extension of the initial production ratio by these suppliers.

Here, we give a short overview on these two mechanisms before we detail them in the following two subsections. Figure 5 contrasts *Acclimate* performances that take one or both of these mechanisms into account to a performance without weakening effects. Scenario 1 (blue ——) assumes that the initial storage content equals five times the initial

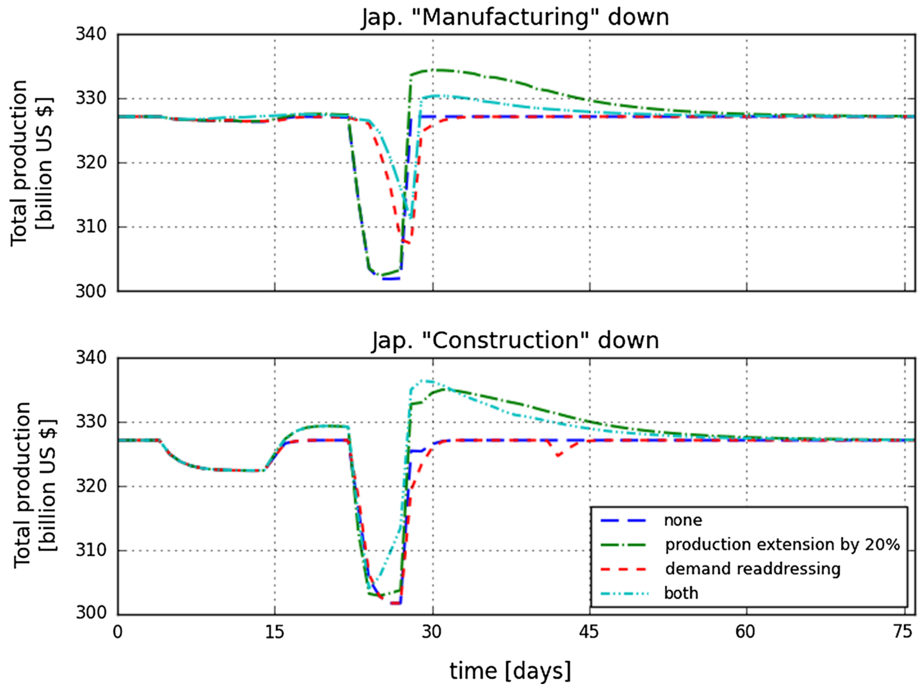

Fig. 5 *Overview on possible dissipation mechanisms: production extension and readdressing of demand*. The Japanese "Manufacturing" and "Construction" sectors are assumed to break down for ten days (days 5–14), respectively. In both scenarios, the possibility of production extension alleviates the disaster-induced production losses during the disaster aftermath (days 23–28). In the first scenario, the readdressing of demand is even more and the combination of both most efficient. In the second scenario, the readdressing of demand has only a weakening effect if it is applied in combination with production extension but then it is again more successful than the pure extension of the initial production ratio

input ($\psi = 5$), that this level can be surpassed by three ($\omega = 3$) and that the storage refill time is 10 ($\gamma = 10$). Moreover, it considers transport-induced time delays. Scenario 2 (green —·—) allows for an additional exceeding of the initial production ratio by 20 % ($\beta = 1.2$). Scenario 3 (red - - -) includes the readdressing of demand where the last demand–supply ratio and the previous demand–supply history are weighted equally ($\varphi = 0.5$). Scenario 4 (turquoise —··—) combines 2 and 3.

Firstly, the Japanese "Manufacturing" sector is assumed to break down from day five until day 14. For the disaster period, *Acclimate* indicates only a small difference between the four scenarios. For the disaster aftermath, it shows that production losses are reduced if each production site can extend its initial production. These losses are even smaller if the demand is readdressed according to the history weight $\varphi = 0.5$. They are minimal if both weakening mechanisms are combined because demand requests can then be addressed most effectively to those production sites that have the capacities (i.e., sufficiently large amounts of stored goods) to make use of the possibility of production extension.

This outcome changes if we analyze the consequences of a breakdown of the Japanese "Construction" sector. Now, *Acclimate* shows that the readdressing of demand without production extension causes even higher production losses than in scenario 1. These different outcomes indicate on the one hand that the effectiveness of demand readdressing might depend on the sector that is assumed to break down or more precisely on the structure of the underlying economic network. On the other hand, the magnitude of the externally imposed damage might play a role. Since the direct production losses caused by a breakdown of the "Construction" sector are higher than those evoked by a shutdown of the "Manufacturing" sector, the readdressing of demand without production extension induces stronger changes in the economic network. These may increase the overall production losses.

3.3 Effect of production extension

In this subsection, we detail the role of production extension, i.e., the possibility of production sites to extend their initial production ratio by a certain factor. Particularly, we focus on the interdependence of the two response mechanisms production extension and demand readdressing to analyze under which conditions production and

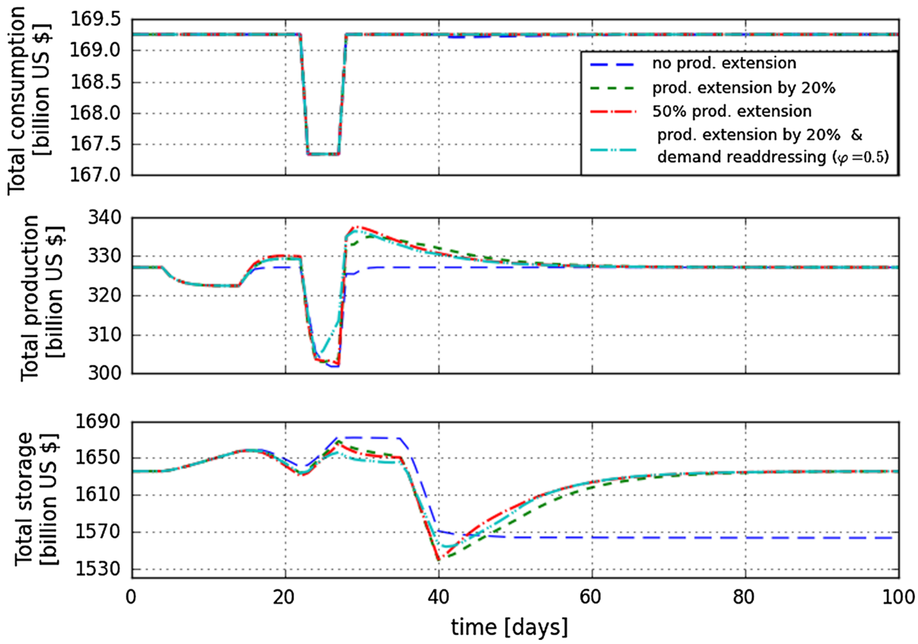

Fig. 6 *Role of production extension on the worldwide recovery of consumption, production and storage contents after an external shock*. It is assumed that the Japanese "Construction" sector breaks down at days 5–14. With regard to production and consumption losses, the possibility of production extension has only a small effect. However, a recovery of the whole system that includes a refilling of storages can only be achieved if there is the possibility to extend the initial production ratio. A raise of the production extension factor from 20 to 50 % enables a quicker refilling of storages but does not lead to smaller production losses. Those are reduced if not only a production extension by 20 % but also a readdressing of demand is possible

consumption losses are minimal and a complete recovery of the economic system is achieved.

Choosing the same forcing and scenario parameter as for the "Construction" sector in Fig. 5, we find that a complete recovery including a refilling of storages can only be achieved in *Acclimate* if an extension of the initial production ratio by a certain factor is possible (Fig. 6, all except blue — —). The external forcing that is temporarily imposed upon the system destroys a certain amount of goods. This loss cannot be compensated unless there is the possibility to feed additional goods into the system by extending the initial production ratio.

Figure 6 further shows that the replenishment of the storages occurs more quickly if the production extension rate increases (red - - - instead of green — · —). With regard to production losses, there is only a very small difference between a production extension by 20 % and one by 50 % and no difference at all concerning consumption losses. Since production sites continuously address their demand according to the initial distribution scheme to their suppliers, they keep considering affected production sites as reliable suppliers. During the disaster period, they are thus consciously lacking a certain amount of inputs while one or more of their other suppliers offering the same good might be able to step in. Figure 6 demonstrates that a production extension by 20 % combined with the possibility to address demand not only in accordance with the initial distribution scheme but also dependent on the last deliveries (turquoise,— · · —) leads to less production losses in *Acclimate* than a production extension by 50 %. On account of a demand distribution scheme that includes recent trade pattern, those suppliers with sufficient storage contents to extend their initial production can be found.

We now examine the effect of different factors of production extension (in the range of 0–20 %) in more detail. Keeping the former model setting, we determine the total amount of production losses and storage deficits that are induced by a ten-day breakdown of varying Japanese sectors ("Manufacturing," "Construction" and "Metal"). For each production extension factor, we add up the discrepancies from the initial production and storage levels occurring during the ten-day breakdown and the subsequent 85 days (recovery phase) and normalize them with respect to the highest difference, respectively. Since the initial production may be surpassed by the production extension factor, production losses can also be negative.

Figure 7 shows that for each scenario a production extension factor can be found such that production losses or storage deficits cannot be further decreased by a higher production extension factor. If we assume that demand is addressed to suppliers according to the initial demand–supply ratio ($\varphi = 1.0$, left column of Fig. 7), a production extension by 5 % (if "Manufacturing" or "Metal" stops

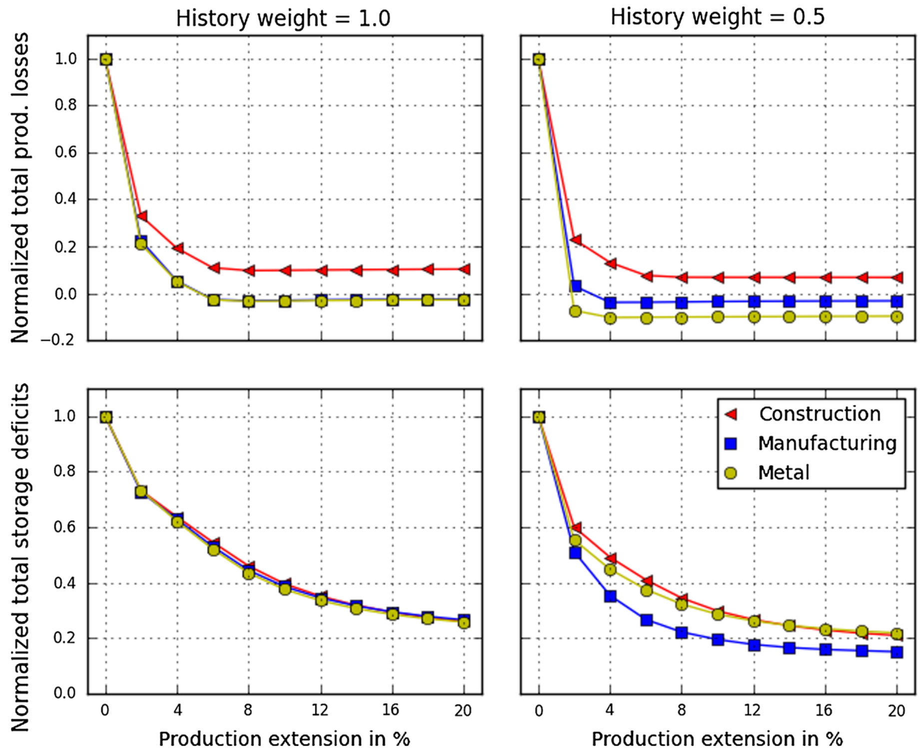

Fig. 7 *Normalized production losses and storage deficits for different production extension factors under two scenarios of demand distribution*. The Japanese "Construction," "Manufacturing" and "Metal" sectors are assumed to break down for ten days, respectively. The total amount of production losses and storage deficits occurring during this time and the following 85 days are added up for each production extension factor and normalized with respect to the highest discrepancy. Production losses and storage deficits begin stagnating at a certain factor of production extension. This factor is smaller if a readdressing of demand is possible

production) or 6 % ("Construction" breakdown) implies the same production losses than a production extension by 20 %. If additionally a readdressing of demand is possible ($\varphi = 0.5$, right column of Fig. 7), the production losses already begin stagnating at a production extension factor of 4 % or 5 %. Regarding storage deficits higher production extension factors are required to achieve the minimal deficit that is possible under the model setting chosen. Again, the stagnation point is achieved at a smaller factor of production extension if a readdressing of demand is possible.

3.4 Effect of demand redistribution

In the last subsections, we already addressed the potentially weakening effect of production redistribution. According to our model setup, a production site redistributes its demand for a certain good among its suppliers if a demand request was not fulfilled satisfactorily by one of these suppliers in the last time step. It determines new demand shares following a certain distribution strategy that is realized by adjusting the history weight parameter φ. This history weight denotes the extent to which the last demand–supply ratio is considered compared to the whole demand–supply history θ, reflecting the initial and, in rising shares, all following demand–supply ratios. If $\varphi = 1$ is chosen, only the initial demand–supply ratio is taken into account and the demand cannot but be distributed according to the initial scheme. In the following, we investigate how production losses and storage deficits vary in dependence on the demand distribution strategy chosen.

As motivated by Sects. 3.2 and 3.3, we particularly analyze the interplay of demand distribution strategy and production extension factor for a ten-day breakdown of the Japanese "Construction," "Manufacturing" and "Metal" sectors, respectively. We first analyze ten different distribution schemes ($\varphi = 0.1, 0.2, \ldots, 1$) by applying our usual scenario parameter and without taking production extension into account ($\beta = 1$). The left column of Fig. 8 shows for each history weight the normalized total production losses and storage deficits (calculated analogously to the normalized production losses and storage deficits in Fig. 7). In case the "Construction" sector is assumed to break down, production losses and storage deficits are minimal in *Acclimate* if the demand is distributed according to the initial scheme ($\varphi = 1$) and maximal for the history weight $\varphi = 0.1$. This trend reverses if additionally a production extension by 20 % (right column of Fig. 8) is possible: Now, production losses are maximal for $\varphi = 1$ and decrease proportionally to the history weight. The readdressing of demand without production extension may increase production losses because in this model setup the suppliers distribute their output proportionally to the demand requests received. This has two consequences. Firstly, if they cannot fulfill all requests, the share that is sent to each buyer is reduced by the same factor. Hence, if one production site requests more while all other buyers maintain their initial requests, they all receive less inputs. This can be regarded as a third, indirect form of damage propagation: Since one production site increases its demand, other production sites have to renounce a certain amount of their inputs. Yet, this effect might play a minor role if the externally imposed production losses are quite small. Secondly, even though the demand readdressing is designed to allocate buyers to those production sites with free capacities, without the possibility of production extension, these free capacities only occur if other buyers request less. Consequently, the effectiveness of demand redistribution strongly depends on the sector that is chosen to break down and the underlying network structure.

Figure 8 demonstrates that for a breakdown of the “Manufacturing” or “Metal” sector, the redistribution of demand may even be advantageous over a large range of history weights if the possibility of production extension is not given. Here, production losses and storage deficits decrease with the history weight down to $\varphi = 0.2$. However, the production losses of both sectors increase considerably for $\varphi = 0.1$. This increase may be explained as follows: Assuming a history weight of $\varphi = 0.1$ in the model setting implies that purchasing managers consider the demand–supply ratio of the last time step to 90 % when distributing their current demand. Since it is likely that their suppliers cannot respond immediately to a higher request, the purchasing managers reallocate their demand requests permanently and the system is highly instable. If the production extension factor is $\beta = 1.2$, the deviation of the current production from the baseline is also highest for $\varphi = 0.1$. Here, suppliers are more likely to be able to satisfy higher requests. As a consequence, the overall production level increases and the storage deficits become larger. In case the “Manufacturing” sector is assumed to break down, production losses and storage deficits are minimal if the production losses are zero instead of negative (for $\varphi = 0.3$). This indicates that for a reduction of production losses and storage deficits, it may not only be important to readdress demand to suppliers with free capacities but also to give them an adequate amount of time to respond to the increase in demand.

All these dynamics will change considerably if the output distribution scheme of a supplier applied in *Acclimate* may also vary, i.e., if production sites can prioritize certain purchasers (e.g., “loyal” or “high-bidding” ones) over others.

4 Conclusions

We presented an extended setup of the numerical model for economic damage propagation *Acclimate*. By integrating response mechanisms that account for the demand-induced backward dynamics in an economic system, we approached a more comprehensive analysis of production failures in a post-disaster scenario. First simulations for idealized sector

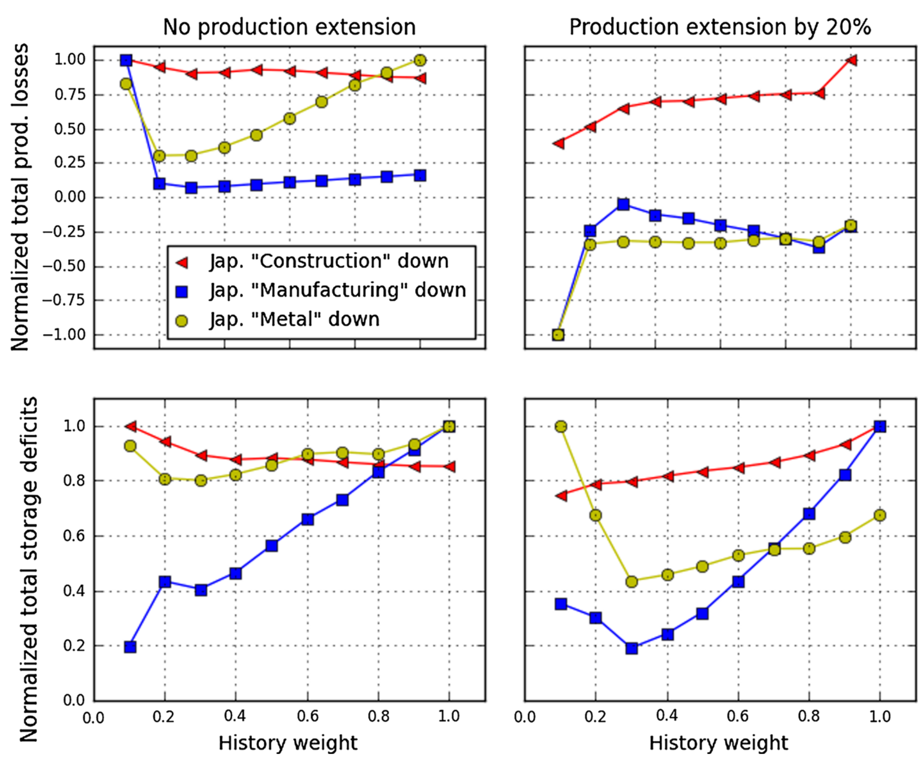

Fig. 8 *Effect of demand readdressing according to different history weights on production losses and storage deficits without and with production extension*. The Japanese “Construction”, “Manufacturing” and “Metal” sectors are assumed to break down for ten days, respectively. The total amount of production losses and storage deficits occurring during this time and the following 85 days are added up for each history weight and normalized with respect to the highest discrepancy. The effectiveness of a demand distribution strategy, i.e., a history weight, highly depends on the sector that is assumed to break down and the possibility of production extension

breakdowns showed that the possibility of immediate production extension does not only reduce economic losses but may also enable a complete recovery of the system. The first effect may be reinforced by a readdressing of demand requests according to a demand–supply history of purchaser and supplier. Up to now, this readdressing only provides a framework for a redistribution of demand among old suppliers. In an upcoming model version, new suppliers will be included into the demand distribution scheme. This extension will make a dynamic restructuring of the initial economic network possible. Further, the model will be extended by a price dynamic to enable a demand distribution strategy that is not only motivated by the reliability of suppliers but also by the prices to which they offer their goods. Similarly, the distribution of output that has been purely availability-limited so far can then also be price-driven.

Besides, the following limitations of our modeling framework have to be addressed in order to effectively use *Acclimate* for an estimation of the indirect effects of an extreme event. First of all, the level of sector and region detail is crucial. In Sect. 3, the model equations intrinsically designed for firms were applied to regional sectors. Although the Eora MRIO database already comprises 27 sectors in 186 countries, this coverage is still too coarse for an appropriate hind- or forecasting of extreme events. With the purpose of refining available MRIO data sectorally and regionally, we developed a routine for data disaggregation (Wenz et al. 2015) and launched the community data project *zeean* (www.zeean.net).

Once a higher sector level is obtained, the introduction of substitution elasticities for inputs might be necessary. At least, a classification of products distinguishing between intermediate inputs and investments goods is expedient to enable a realistic application of certain *Acclimate* routines, e.g., the assumption of perfect complementarity. Such a classification will also allow for a better calibration of scenario parameters such as storage capacities and production extension capabilities. Data sources to assess parameter and scenarios for hind- and forecasting have to be explored. Further, simulations with *Acclimate* should be based on a more realistic representation of the transportation network to take another important factor for supply failures into account: the destruction of critical infrastructure. Finally, the model setup could consider that an additional amount of reconstruction and repair efforts might be required to overcome a disaster.

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Appendix 1: *Acclimate* agents and parameter

See Table 1.

Table 1 Alphabetical list of all *Acclimate* agents and parameter used in this paper including their units

Parameters	Name	Unit
$c^{(t)}_{i\to j_f s}$	Consumption ratio	Ratio
$C^{(t)}_{i\to j_f s}$	Consumption	Flow
$D^{(t)}_{i\leftarrow js}$	Commodity demand	Quantity/time
$D^{(t)}_{ir\leftarrow js}$	Demand request	Quantity/time
$I^{(t)}_{i\to js}$	Input flow	Quantity/time
$p^{(t)}_{js}$	Production ratio	Ratio
$\hat{p}^{(t)}_{js}$	Possible production ratio	Ratio
$\tilde{p}^{(t)}_{js}$	Target production ratio	Ratio
$S^{(t)}_{i\to js}$	Input storage	Quantity
$T^{(t)}_{ir\longrightarrow_b js}$	Transport chain link	Quantity/time
$T^{(t)}_{ir\to js}$	Transport stock	Quantity
$U^{(t)}_{i\to js}$	Used flow	Quantity/time
$\hat{U}^{(t)}_{i\to js}$	Possible used flow	Quantity/time
$\tilde{U}^{(t)}_{i\to js}$	Target used flow	Quantity/time
$X^{(t)}_{js}$	Production	Quantity/time
$Z^{(t)}_{ir\to j_f s}$	Final demand flow	Quantity/time
$Z^{(t)}_{ir\to js}$	Intersectoral flow	Quantity/time
Δt	Time step for numerical computation	Time
$\beta_{js} \geq 1$	Production extension factor	Ratio
$\gamma_{i\to js} \geq \Delta t$	Input storage refill enforcement	Time
$\vartheta^{(t-1)}_{ir\to js} \in [0,1]$	Demand–supply ratio	Ratio
$\theta^{(t+1)}_{ir\to js} \in [0,1]$	Demand–supply history	Ratio
$\lambda^{(t)}_{js} \in [0,1]$	Forcing on production site (on β_{js})	Ratio
$\lambda^{(t+1)}_{i\to j_f s} \in [0,1]$	Forcing on consumption site	Ratio
$\mu^{(t)}_{i\to js} \in [0,1]$	Forcing on storage	Ratio
$\tau_{ir\to js} \geq \Delta t$	Transit time	Time
$\varphi \in]0,1]$	History weight	Ratio
$\Psi_{i\to js}$	Input storage fill factor	Time
$\omega_i \geq 1$	Upper storage limit	Ratio

Appendix 2: Linkage between final demand, GDP and value added (including taxes)

In an MRIO table framework, the total value added of a certain region equals its GDP, i.e., the sum of all its final demand and export flows minus its import flows:

Jonkeren O, Giannopoulos G (2014) Analysing critical infrastructure failure with a resilience inoperability input–output model. Econ Syst Res 26:39–59. doi:10.1080/09535314.2013.872604

Kajitani Y, Tatano H (2014) Estimation of production capacity loss rate after the great East Japan earthquake and tsunami in 2011. Econ Syst Res 26:13–38. doi:10.1080/09535314.2013.872081

$$\overbrace{\overbrace{\sum_i \sum_r z_{ir\to j_f s}}^{\text{final demand}} + \overbrace{\sum_j \sum_k \sum_{u\neq s} z_{js\to ku} + \sum_j \sum_{u \neq s} z_{js\to k_f u}}^{\text{Exports}} - \overbrace{\left(\sum_i \sum_r \sum_j z_{ir\to js} + \sum_i \sum_{r\neq s} z_{ir\to j_f s}\right)}^{\text{Imports}}}^{\text{GDP of region } s}$$

$$= \sum_i z_{is\to j_f s} + \sum_j \sum_k \sum_s z_{js\to ku} - \sum_k \sum_j z_{js\to ku} + \sum_u \sum_j z_{js\to k_f u} - \sum_j z_{js\to j_f s} - \sum_i \sum_r \sum_j z_{ir\to js}$$
$$+ \sum_i \sum_j z_{is\to js}$$

$$= \underbrace{\underbrace{\sum_j \sum_u \left(\sum_k z_{js\to ku} + z_{js\to k_f u}\right)}_{\text{total outputs of } s} - \underbrace{\sum_i \sum_r \sum_j z_{ir\to js}}_{\text{total inputs of } s}}_{\text{total value added of region } s}.$$

References

Bierkandt R, Wenz L, Willner SN, Levermann A (2014) Acclimate—a model for economic damage propagation. Part 1: basic formulation of damage transfer within a global supply network and damage conserving dynamics. Environ Syst Decis. doi:10.1007/s10669-014-9523-4

Bouwer LM, Crompton RP, Faust E, Höppe P, Piekke RA Jr (2007) Confronting Disaster Losses. Science 318:753. doi:10.1126/science.1149628

Cochrane H (1997) Economic impacts of a Midwestern earthquake. Q Publ NCEER 11:1–20

Haddad E, Okuyama Y (2012) Spatial propagation of the economic impacts of bombing: the case of the 2006 war in Lebanon. University of Sao Paulo 2012_19

Haddad E, Teixeira E (2013) Economic impacts of natural disasters in megacities: the case of floods in São Paulo, Brazil. ERSA Conf Pap 1–20

Hallegatte S (2008) An adaptive regional input–output model and its application to the assessment of the economic cost of Katrina. Risk Anal 28:779–799

Hallegatte S (2014) Modeling the roles of heterogeneity, substitution, and inventories in the assessment of natural disaster economic costs. Risk Anal 34:152–167

Hirabayashi Y, Mahendran R (2013) Global flood risk under climate change. Nat Clim Chang 3:816–821. doi:10.1038/NCLIMATE1911

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the Intergovernmental Panel on Climate Change. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds). Cambridge University Press, Cambridge

Lenzen M, Kanemoto K, Moran D, Geschke A (2012) Mapping the structure of the world economy. Environ Sci Technol 46:8374–8381. doi:10.1021/es300171x

Levermann A (2014) Make supply chains climate-smart. Nature 504:27–29

Mendelsohn R, Emanuel K, Chonabayashi S, Bakkensen L (2012) The impact of climate change on global tropical cyclone damage. Nat Clim Chang 2:205–209. doi:10.1038/nclimate1357

Miller RE, Blair PD (2009) Input–output analysis: foundations and extensions. Cambridge University Press, Cambridge

Narayanan B, Aguiar A, McDougalL R (2012) Global trade, assistance and production: the GTAP8 database. Purdue University. [Online] http://www.gtap.agecon.purdue.edu/databases/v8/v8_doco.asp

Okuyama Y, Sahin S (2009) Impact estimation of disasters a global aggregate for 1960 to 2007. Worldbank Open Knowl. Repos

Okuyama Y, Santos JR (2014) Disaster impact and input–output analysis. Econ Syst Res 26:1–12. doi:10.1080/09535314.2013.871505

Peduzzi P, Chatenoux B, Dao H, De Bono A, Herold C, Kossin J, Mouton F, Nordbeck O (2012) Global trends in tropical cyclone risk. Nat Clim Chang 2:289–294. doi:10.1038/nclimate1410

Rahmstorf S, Coumou D (2012) Increase of extreme events in a warming world. Proc Natl Acad Sci USA 109:4708

Rose A (2004a) Economic principles, issues, and research priorities in hazard loss estimation. Model Spat Econ Impacts Disasters 13–36

Rose A (2004b) Defining and measuring economic resilience to earthquakes. Disaster Prev Manag 13:307–314

Rose A (2007) Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions. Environ Hazards 7:383–398. doi:10.1016/j.envhaz.2007.10.001

Rose A, Dongsoon L (2002) Business interruption losses from natural hazards: conceptual and methodological issues in the case of the

Northridge earthquake. Glob Environ Chang B Environ Hazards 4:1–14

Schellnhuber H-J et al (2012) Turn down the heat–why a 4 C warmer world must be avoided. World Bank

Sea Rates (2013) International container shipping | freight broker and forwarder. distances and transit times. [Online] www.searates.com/reference/portdistance. Accessed 11 Feb 2014

Sternberg T (2012) Chinese drought, bread and the Arab Spring. Appl Geogr 34:519–524

Strzepek K, Yohe G, Neumann J, Boehlert B (2010) Characterizing changes in drought risk for the United States from climate change. Environ Res Lett 5:044012. doi:10.1088/1748-9326/5/4/044012

Timmer MP (2012) The world input–output database (WIOD). Contents, sources and methods. [Online] www.wiod.org

United Nations Department of Humanitarian Affairs (1992) Internationally agreed glossary of basic terms related to disaster management. United Nations Department of Humanitarian Affairs, Geneva

Van Der Veen A (2004) Disasters and economic damage: macro, meso and micro approaches. Disaster Prev Manag 13:274–279. doi:10.1108/09653560410556483

Van Der Veen A, Logtmeijer C (2005) Economic hotspots: visualizing vulnerability to flooding. Nat Hazards 36:65–80. doi:10.1007/s11069-004-4542-y

Wenz L, Willner SN, Radebach A, Bierkandt R, Steckel JC, Levermann A (2015) Regional and sectoral disaggregation of multi-regional input–output tables—a flexible algorithm. Econ Syst Res 27. doi:10.1080/09535314.2014.987731

Wiedmann T, Wilting HC, Lenzen M, Lutter S, Palm V (2011) Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. Ecol Econ 70:1937–1945